INDOOR AIR QUALITY AND VENTILATION

Edited by F. Lunau
and G.L. Reynolds

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PREFACE

The indoor environment has traditionally been regarded as a refuge from pollution in the air outdoors. However, it has recently become apparent that indoor air quality may be poor and in some cases pollution levels may exceed those outdoors. Although in both temperate and warm climates indoor air quality will be considerably affected by external air quality and meteorological conditions, the degree of influence will largely be dependant upon building design together with ventilation and air conditioning practices.

Historically, indoor air quality problems have always existed, for example in the form of mould and condensation formation, transmission of respirable diseases and production of combustion by-products; however, pollution problems have intensified over the past two decades. Such deterioration in indoor air quality is likely to be real rather than a reflection of an increasing ability to measure trace pollutants and may largely be attributed to the implementation of energy conservation measures in many buildings leading to a reduction in ventilation combined with the introduction of an increasing number of synthetic materials from which a release or evaporation of volatile organic compounds may occur.

The range of substances which may pollute the indoor air is diverse and sources of pollutants may be natural as well as anthropogenic in origin. Pollutants of concern include volatile organic compounds, products of combustion, mineral fibres, radioactive radon gas and biological contamination by microorganisms and allergens. In addition, a variety of more localised problems relating to occupational exposure to industrial pollutants may be encountered in the workplace.

This book addresses the scientific, design and health aspects of indoor air quality. Each chapter has been compiled from a number of thematically consistent presentations made at the Indoor Air Quality and Ventilation Conference held in Lisbon, Portugal, between 24th and 26th April 1990 under the auspices of the Technical Committee including: J.J. Amaral Mendes, G. Aubertin, R.M. Harrison, F. He, Y.S. Kim, G.B. Leslie, S. Liao, P. O'Sullivan, R. Perry, F.J. Pires Santana, B.R. Reverente, F.J.C. Roe, E. Tsani-Bazaca and M. Wongphanich.

The editors gratefully acknowledge the work of this Committee.

F.W. Lunau
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ESTIMATION OF EFFECT OF ENVIRONMENTAL TOBACCO SMOKE ON AIR QUALITY WITHIN PASSENGER CABINS OF COMMERCIAL AIRCRAFT. II.

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ABSTRACT

To assess exposures to environmental tobacco smoke (ETS), concentrations of nicotine, respirable suspended particles (RSP), and ultraviolet particulate matter (UVPM) were determined in passenger cabins of commercial aircraft. Arithmetic mean concentrations of nicotine, RSP, and UVPM in nonsmoking sections were 2.3, 15, and 7 $\mu g\ m^{-3}$, respectively; corresponding arithmetic mean concentrations in smoking sections were 10.6, 39, and 26 $\mu g\ m^{-3}$, respectively. The effect of smoker segregation on ETS was shown by statistically significant differences ($P < 0.05$) between concentrations of nicotine, RSP, and UVPM measured in nonsmoking and smoking sections of the aircraft.

INTRODUCTION

The earlier report in this series [1] addressed results from measurements of vapor phase nicotine in passenger cabins of narrow-bodied B727-200, B737-200, and B737-300 aircraft on U.S. domestic flights. Vapor phase nicotine was employed as the indicator of environmental tobacco smoke (ETS) because it is specific to ETS and because experiments have shown that approximately 95% of the nicotine associated with ETS exists in the vapor phase [2, 3]. Results of this earlier investigation showed that smoker segregation significantly reduces exposure of passengers in non-smoking sections of these aircraft to ETS and that the design and operation of the aircraft heating, ventilating, and air conditioning (HVAC) systems could account for such reduction.

Since the promulgation of U.S. regulations restricting smoking [4], no investigation of ETS in wide-bodied aircraft has been reported. Results from measurements of ETS performed in narrow-bodied aircraft are not expected to be representative of ETS in wide-bodied aircraft because of differences in the design and operation of heating, ventilating, and air conditioning (HVAC) systems, seating patterns, passenger loads, and lengths of flights. To assess more completely the effect of cigarette smoking on air quality in passenger cabins of commercial aircraft, we conducted investigations in wide-bodied aircraft during long flights. Compared to earlier surveys, these investigations used more sophisticated sampling equipment capable of determining ETS constituents in addition to nicotine. For the investigations reported here, sampling was conducted throughout passengers cabins in both smoking and non-smoking sections and in all classes of service on board B747 aircraft.

Additional ETS markers compared to nicotine study

EXPERIMENTAL

Aircraft

Investigations were performed during December 1987 in one B747LR-100 and three B747LR-200s on non-stop, regularly scheduled, weekday flights connecting New York (Kennedy), Tokyo (Narita), and Hong Kong (Kai Tak). B747LR-100s and B747LR-200s have seating capacities of 392 and 362 revenue passengers, respectively.

Although constructed at different times ranging from May 1970 to June 1983, the Boeing 747LR-100 and -200 aircraft studied have HVAC systems of the same design (5). Each system has three air conditioning units feeding into a common plenum chamber. Air from the plenum chamber flows to five air conditioning zones. Zone 1 includes the cockpit, zones 2, 3, and 4, the passenger cabin on the main level; and zone 5, the passenger cabin on the upper deck. Air can be recirculated within a given zone, but is never recirculated between the cabin and the plenum chamber.

Within the passenger cabin, air enters from outlets high on the side walls, flows toward the center of the cabin where it converges, and then flows down and back along the floor to the walls. At the walls the air divides, one portion exiting through the side vents into the lower cargo compartment and the other rising to join the incoming air from ceiling-level ducts.

The major exhaust route is through outflow valves located in the aft ventral area of the fuselage. Air from the passenger cabin reaches these valves by flowing into the side-wall grilles near the cabin floor and moving aft through the lower cargo compartment. When all three air conditioning packs are in operation, air is exhausted at about 220 $m^3 min^{-1}$ by this route. Another vent system, which serves the lavatories, galleys and staircase, exhausts about 30 $m^3 min^{-1}$. Lastly, a small amount of air leaves the cabin through minor leaks, occurring primarily at door seals. During the investigation, all three air conditioning packs operated automatically at full rate throughout every flight. Based on the exhaust flow rates identified above, a maximum flow rate of 250 $m^3 min^{-1}$ through the cabin is presumed.

Because the aircraft design causes air to be taken in somewhat more rapidly by the floor-level grilles in the aft sections than by the floor-level grilles in the forward sections, there is a slight tendency for the general air movement in the cabin to be from front to rear. Thus, the general direction of air flow through the cabin is a diagonal movement from ceiling to floor with a small velocity from the front of the cabin to the rear.

Sampling Locations

Ten sampling locations were randomly selected for each of the four flights. The distribution of sampling locations was two in first class and four in each of the business and economy classes with equal numbers in smoking and non-smoking sections of each class. Window and bulkhead seats were not chosen because of the possibility that wall effects (6) would lead to biased estimates of exposure.

Two samples were collected at each location on flights between New York and Tokyo. Collection of the first sample began after the aircraft doors were closed and ended about mid way into the flight, when collection of the second sample started. Collection of the second sample ended when the aircraft doors were opened upon arrival at the gate. On flights between Tokyo and Hong Kong, only one sample was collected at each location.

Flight crews were informed of the investigation before each departure. Flight data were obtained and cigarette butts were collected at the end of each flight. Aircraft were cleaned by maintenance personnel before the sampling team boarded each flight.

Sampling methods and procedures

Portable air sampling systems (PASS s) [7, 8] were used to collect integrated samples of vapor phase nicotine, RSP, and UV-PM and to monitor CO, temperature, and barometric pressure. The PASS is an area sampling device, powered by batteries and designed to appear as an ordinary briefcase. During operation, the PASS remains closed and the noise it makes is imperceptible in the cabin. The briefcase exterior includes an on-off switch positioned under the handle and inlet and exhaust ports positioned diametrically at the corners. Added hardware is brass selected to match the normal briefcase hardware. The above features are intended to reduce the possibility that sampling will influence the smoking behavior of passengers.

The PASS was tested to ensure that its operation would not interfere with avionics. Test results showed that the PASS conforms with Federal Aviation Administration specifications.

For sampling in the aircraft, each PASS was placed upright in its assigned seat and secured with a seat belt fastened through its handle. In this position the PASS sampled as close as possible to the breathing zones of passengers. Each PASS was attended by one member of the sampling team to prevent its being disturbed and to assure that each measurement began and ended on time.

The method used to sample nicotine has been described before [1]. Major components of the sampling system include a sorbent tube containing XAD-4 resin (SKC Inc., Eighty-Four, PA) connected by rubber tubing to a constant-flow sampling pump (SKC Inc.) operated at 1 L min^{-1}. Particulate matter samples were collected by the method described by Conner *et al.* [9]; this method employs a system comprising an impactor separating at 3.5 µm, a filter assembly containing a 37-mm Fluoropore membrane filter with a pore size of 1.0 µm (Millipore, Corp., Bedford, MA), and a constant-flow sampling pump (SKC Inc.) operated at 2 L min^{-1}. Pumps were calibrated before and after sample collection with a film flow meter. Samples were invalidated if calibration checks showed deviations from average flow greater than 10%.

CO monitoring systems were developed by modifying commercially available, passive sensors to operate with sampling pumps [7, 8]. CO detectors (Neotronics, N.A., Gainesville, GA) are fitted with sampling lines and sampling pumps (Gilian, Inc., Wayne, NJ) and provided with a voltage-regulated power supply to maintain constant flow during sampling. The detector is interfaced to a 21X Micrologger (Campbell Scientific, Inc., Logan, UT) programmed to record data each minute. Recorded data were transferred to cassette tape and then to a personal computer for analysis. CO monitoring systems were calibrated with gaseous standards before and after sample collection.

Analytical Procedure

Nicotine was quantified with the method described by Ogden *et al.* [10]. Nicotine collected on XAD-4 resin is desorbed in 2 mL ethyl acetate containing 0.01% (v/v) triethylamine, which neutralizes acidic sites on surfaces of analytical glassware. Analyses are performed with a Model 5880A gas chromatograph equipped with a nitrogen-selective detector (Hewlett-Packard, Avondale, PA). Chromatography is done on a 30 m X 0.53 mm inside diameter, fused silica capillary column coated with a 1.5 micron film of DB-5 (5% phenyl methylpolysiloxane) (J&W Scientific, Inc., Folsom, CA). Quinoline is employed as an internal standard. For each sample, the front and rear segments of XAD-4 resin are analyzed separately to assess breakthrough; none was observed. Desorption efficiency was quantified by the method described by the U.S. National Institute of Occupational Safety and Health (NIOSH) [11]. The nicotine method has been collaboratively tested [12].

RSP was quantified gravimetrically according to method described Conner *et al.* [9]. Filters with and without samples are conditioned at room temperature and 50% relative humidity for at least 12 hours before weighing. Static charges are removed by holding filters and samples under an anti-static device (Staticmaster, Model No. 2U500, Nuclear Products Co., El Monte, CA) for at least one minute before each weighing. Weights are

measured with a balance having a readability of one microgram (Mettler M), Mettler Instrument Corp., Highstown, NJ) and having an anti-static device attached to the interior wall. Each gravimetric result is the average of at least five separate weighings.

UVPM was quantified as described by Conner et al. (9). After RSP is determined, the sample and filter are extracted with 4 mL methanol and a 50-µL aliquot of the extract is injected into a columnless liquid chromatographic system equipped with an ultraviolet detector measuring absorption at 325 nm. Masses of UVPM are computed from a standard calibration curve derived from a series of ETS concentrations prepared in an environmental chamber (13). For the work reported here, methanolic solutions of 2,2',4,4'- tetrahydroxybenzophenone (Aldrich, Milwaukee, WI) were used as secondary standards (9). Ingebrethsen et al. (9, 14) have shown that results from RSP and UVPM methods are unbiased relative to results from piezoelectric balances.

RESULTS AND DISCUSSION

Table I presents results from determinations of concentrations of nicotine, RSP, and UVPM in nonsmoking (NS) and smoking sections (S). Classes of service are: first class, FClass; executive, Exec; and economy, Econ. Flights are identified as follows: flight 1, Tokyo to Hong Kong; flight 2, Hong Kong to Tokyo; flight 5, New York to Tokyo; and flight 8, Tokyo to New York. Data invalidated because of calibration results are designated not available (NA).

TABLE I. Results from Determinations of Nicotine, RSP, and UVPM Concentrations in B747 Aircraft

No.	Class	Section	Flight	Sample	Concentration, µg m^{-3} Nicotine	RSP	UVPM
1	Econ	S	1		25.7	119	88
2	Exec	S	1		NA	102	102
3	Exec	S	1		NA	50	47
4	Econ	S	1		31.4	59	59
5	FClass	S	1		11.4	33	20
6	Exec	NS	1		3.3	3	3
7	FClass	NS	1		NA	3	3
8	Econ	NS	1		0.1	3	3
9	Econ	NS	1		12.4	98	30
10	Exec	NS	1		2.9	3	3
11	FClass	S	2		9.0	5	5
12	Econ	S	2		42.7	185	113
13	Exec	S	3		9.4	5	5
14	Econ	S	3		NA	31	31
15	Exec	S	3		14.9	NA	NA
16	Exec	NS	3		2.9	63	14
17	FClass	NS	3		6.1	31	19
18	Econ	NS	3		4.6	35	18
19	Exec	NS	3		2.7	48	13
20	Econ	NS	3		NA	5	5
21	FClass	S	5	1	10.6	21	21
23	Exec	S	5	1	7.6	56	15
23	Exec	S	5	1	1.8	23	5
24	Econ	S	5	1	NA	35	35
25	Econ	S	5	1	NA	32	19

TABLE I. Results from Determinations of Nicotine, RSP, and UVPM Concentrations in B747 Aircraft (continued)

No.	Class	Section	Flight	Sample	Concentration, µg m⁻³ Nicotine	RSP	UVPM
26	Econ	NS	5	1	NA	2	2
27	Exec	NS	5	1	0.8	6	6
28	Exec	NS	5	1	0.7	26	4
29	FClass	NS	5	1	0.1	11	3
30	Econ	NS	5	1	1.8	2	2
31	Econ	S	5	2	NA	3	3
32	Exec	S	5	2	2.1	3	3
33	FClass	S	5	2	4.7	47	15
34	Exec	S	5	2	8.8	42	4
35	Econ	S	5	2	NA	23	23
36	Econ	NS	5	2	NA	24	22
37	FClass	NS	5	2	0.1	5	3
38	Exec	NS	5	2	0.7	8	4
39	Econ	NS	5	2	3.7	7	7
40	Exec	NS	5	2	0.6	24	9
41	Exec	S	8	1	13.9	28	28
42	Exec	S	8	1	7.2	26	22
43	Econ	S	8	1	3.9	26	9
44	Econ	S	8	1	4.3	3	3
45	FClass	S	8	1	NA	55	20
46	Exec	NS	8	1	1.1	NA	NA
47	FClass	NS	8	1	0.3	3	3
48	Econ	NS	8	1	4.6	3	3
49	Exec	NS	8	1	1.0	3	3
50	Econ	NS	8	1	NA	8	8
51	Exec	S	8	2	5.9	63	21
52	Econ	S	8	2	1.8	30	6
53	Exec	S	8	2	3.5	19	14
54	Econ	S	8	2	1.8	3	3
55	FClass	S	8	2	NA	3	3
56	Exec	NS	8	2	0.6	NA	NA
57	Econ	NS	8	2	2.2	9	9
58	Exec	NS	8	2	0.5	3	3
59	FClass	NS	8	2	0.1	3	3
60	Econ	NS	8	2	NA	2	2

The CO monitoring systems provided no valid data. Experiments done after the study showed that low relative humidity levels, such as existed in the aircraft cabins, substantially shorten the working life of the CO sensor used by the PASS. Had CO data been obtained, it might have been possible to address issues regarding irritation and annoyance from exposure to ETS.

Goodness of fit tests were used to assess the form of the concentration data. Results indicate that the log normal distribution describes the data better than the normal distribution. Table II provides, by section, summary statistics including the arithmetic and geometric means, maximum and minimum values, and number of samples.

Table II. Summary of Results from Samples Collected in Non-Smoking (NS) and Smoking (S) Sections of B747LR-100 and B747LR-200 Aircraft

	Concentration, µg m^{-3}					
	Nicotine		RSP		UV-PM	
	NS	S	NS	S	NS	S
Mean						
arithmetic	2.3	10.4	15	39	7	24
geometric	1.1	7.1	8	23	5	14
Max	12.4	42.7	98	184	30	113
Min	0.1	1.8	2	3	2	3
N	24	21	38	39	28	28

Statistical analyses employing ANOVA were done to test for differences between mean concentrations (both arithmetic and geometric) of nicotine, RSP, and UV-PM measured in sections and classes of service. Results indicate no statistically significant difference ($P > 0.05$) in concentrations of ETS indicators between classes of service. Class-by-section interactions (Class * Section) also were found not to be significant ($P > 0.05$) for the three indicators. Statistically significant differences are shown between smoking and non-smoking sections for nicotine, RSP, and UVPM. P-values for analyses of the log transformed results are as follows: nicotine, $P = 0.0001$; RSP, $P = 0.0019$; and UVPM, $P = 0.0007$. P-values for the non-transformed results are similar: nicotine, $P = 0.0009$; RSP, 0.0166; and UVPM, 0.0086.

The finding that smoker segregation reduces exposure of passengers seated in non-smoking sections is consistent with results from investigations performed in narrow-bodied aircraft (1, 15, 16, 17). Additionally, this finding is in line with the design and operation of ventilation systems for B747LR-100 and -200 aircraft which are designed to provide more than 17 air changes per hour.

Class-by-section interaction statistics can indicate trends in ETS concentrations going from first class to economy class. The absence of significant class-by-section interaction also is consistent with the design of the ventilation system: air is intended to be uniformly distributed throughout the cabin with flow being predominantly from ceiling to floor with little fore to aft movement.

Nicotine results agree with those previously reported in connection with aircraft cabins. Muramatsu et al. (15, 16) used personal sampling devices to collect nicotine. They reported arithmetic mean concentrations of 11.8 and 3.3 µg m^{-3} at smoking seats and non-smoking seats, respectively. The mean nicotine concentrations for the two sections were statistically different ($p \leq 0.01$) (17). Our earlier investigation (1) of B737-200, B737-200, and B737-100 aircraft reported geometric mean nicotine concentrations of 9.2 µg m^{-3} in smoking sections and 1.5 µg m^{-3} in non-smoking sections. Additionally, statistical analyses showed that the difference between nicotine concentrations measured in the sections was significant.

RSP results for smoking sections are similar to those jointly reported by the U.S. Department of Health, Education and Welfare (DHEW) and U.S. Department of Transportation (DOT) (18). For that investigation, RSP concentrations ranged from none detected to 120 µg m^{-3} with an arithmetic mean of 40 µg m^{-3}. Such similarity might be expected because the DHEW/DOT investigated wide-bodied aircraft. However, these investigations were performed in 1971 when smoking demographics were different and before the promulgation of regulations segregating smokers; thus, the basis for comparison is limited.

Mean concentrations of RSP and UV-PM agree closely. This agreement is expected in view of the absence of significant sources of RSP either within or outside of the aircraft, with the exception of ETS. The differences between geometric mean concentrations of UVPM and RSP measured in smoking and non-smoking sections suggest that background concentrations of RSP in the absence of ETS range between 3 and 9 $\mu g\ m^{-3}$.

Results reported for measurements conducted in non-smoking sections do not represent no smoking conditions. On several occasions during the investigation, passengers seated in non-smoking sections were observed smoking. Indeed, the highest concentrations of nicotine, RSP, and UVPM found in non-smoking sections are associated with just such a situation.

Table III gives information on numbers of passengers and smoking rates for the four flights. Smoking rates are fairly uniform, ranging from 0.28 to 0.37 cigarette passenger^{-1} h^{-1}. It was desired to quantify smoking rates in terms of cigarettes smoking passenger^{-1} h^{-1}; however, occurrence of smoking in non-smoking sections precluded such computations. From data reported by the DHEW/DOT (18) in 1971, smoking rates of 0.4 and 3.6 cigarette passenger^{-1} h^{-1} are computed for domestic flights and for transcontinental flights involving military personnel, respectively. A smoking rate of 0.735 cigarette passenger^{-1} h^{-1} is calculated from data reported in 1961 by Halfpenny and Starrett (19). These rates (18, 19) are higher than those measured for the present investigation, as might be expected, owing to changes in smoking demographics that have occurred since these earlier measurements were reported.

Table III. Smoking Rate Data and Results

flight	average sampling time, min	total no. passengers	no. cigarettes	smoking rate, cigt passenger^{-1} h^{-1}
New York to Tokyo	787	170	619	0.28
Tokyo to Hong Kong	294	252	304	0.29
Hong Kong to Tokyo	203	287	357	0.37
Tokyo to New York	767	96	306	0.28

The RSP and nicotine data reveal one of the limitations of RSP to nicotine ratios when used to evaluate results (20). Repace and Lowrey (21) assume an RSP to nicotine ratio of 7:1 to estimate RSP concentrations from concentrations of nicotine measured in aircraft cabins. Data for the present study give a ratio of 4:1. Factors affecting both terms of the ratio can explain this difference. For ground level environments, the RSP term of the RSP to nicotine ratio generally will be biased high, overestimating ETS, because RSP does not apportion for ETS. In contrast to ground level environments, concentrations of RSP in aircraft cabins are affected less by non-ETS sources; consequently, the RSP term of the RSP to nicotine ratio should better indicate ETS and the ratio should tend to be less than that for ground level environments where the density of smokers is similar.

Lastly, an appreciable background concentration attributable to desorption of nicotine from walls and fabrics might exist within the aircraft cabins. Although neither we nor other researchers have investigated the nicotine background in aircraft cabins, Eudy et al. (22) found a background concentration of approximately 1 $\mu g\ m^{-3}$ in a restaurant having an adjoining bar. Higher background concentrations of nicotine might exist in aircraft cabins compared to ground level environments such as offices and restaurants because aircraft cabins have a greater density of smokers where smoking can occur continuously and a greater surface to volume ratio.

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